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Synthesis of Contributed Simulations for OREX Test Cases

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Synthesis of Contributed Simulations for OREX Test Cases

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Abstract

A synthesis is presented of the computer simulations of the flow over the Orbital Reentry Vehicle (ORV) at the 92.8 km and 63.6 km Earth altitude trajectory points that were discussed at the First Europe-U.S. High Speed Flow Field Database Workshop Part II, Napoli, Italy, November 1997. For the materials used on the surface of ORV, the non-catalytic wall condition is appropriate at 92.8 km and the finite-rate catalytic wall condition at 63.6 km. Additional simulations are required for establishing the independency of the discussed results from numerics. The proper modeling of natural phenomena needs further sensitivity studies. The uncertainties of inferred flight data are lacking for a proper evaluation of the presented results.

Introduction

The Orbital Reentry Experiment (OREX) was conducted jointly by the National Space Development Agency (NASDA), Japan, and the National Aerospace Laboratory (NAL), Japan, in 1994 (ref. 1). This experiment provided electron number density, surface heat flux, and surface pressure at altitudes ranging from 105 to 48.4 km. Figure 1 shows the shape of Orbital Reentry Vehicle (ORV) and measurement locations for electron number density. OREX data are the only flight data considered in the First Europe-U.S. (or U.S.-Europe) High Speed Flow Field (HSFF) Database Workshop.

Numerous computations have been made to compare computed results with flight data and to improve the modeling of natural phenomena in the computations (for example, see the papers on OREX in refs. 2, 3). For the present synthesis, a few lessons learned from those computations are considered.

At the First U.S.-Europe HSFF Database Workshop, Part I, Houston, U.S.A., November 1995, two flight conditions were considered: (1) V_∞ = 7450 m/sec, T_∞ = 186.9 K, and p_∞ = 0.169 N/m^2; and (2) V_∞ = 5562 m/sec, T_∞ = 248.1 K, and p_∞ = 23.60 N/m^2. These conditions are comparable to those considered in Part II of this workshop (table 1). A synthesis of the computations presented in Part I is not available, as a result, it cannot be determined if the credibility of the simulated reality was improved in Part II.

The prescribed conditions for Case T9-97.1 are questionable. The flight time should be 7391.0 sec instead of 7396 sec, if data are taken approximately every 10 sec starting at flight time of 7361.0 sec (as stated in refs. 4, 5). The free-stream velocity should be 7454.0 m/sec instead of 7545.0 m/sec. This difference between the free-stream velocity as provided by Yukimitsu Yamamoto, NAL, for Case T9-97.1 and that previously reported is not resolved here.

The atmospheric data were not collected by OREX. In Part I, the free-stream pressure for Case (1) is based on the 1976 U.S. standard atmosphere. In Part II, this quantity is 0.1086 N/m^2, as determined from the Jacchia atmospheric model (ref. 6). The free-stream density is 3.0090 x 10^{-6} kg/m^3 based on the 1976 U.S. standard atmosphere. It is 1.9465 x 10^{-6} kg/m^3 according to the Jacchia model. The latter model was used in most of previous high-altitude studies.

All computations were carried out with prescribed (inferred—that is, derived) wall temperature distributions at 41 locations along the body starting from the stagnation point. The computed results of different investigators are compared with each other and with inferred flight data. These inferred temperature distributions and inferred flight heating rates were determined using simulation models and raw flight data.

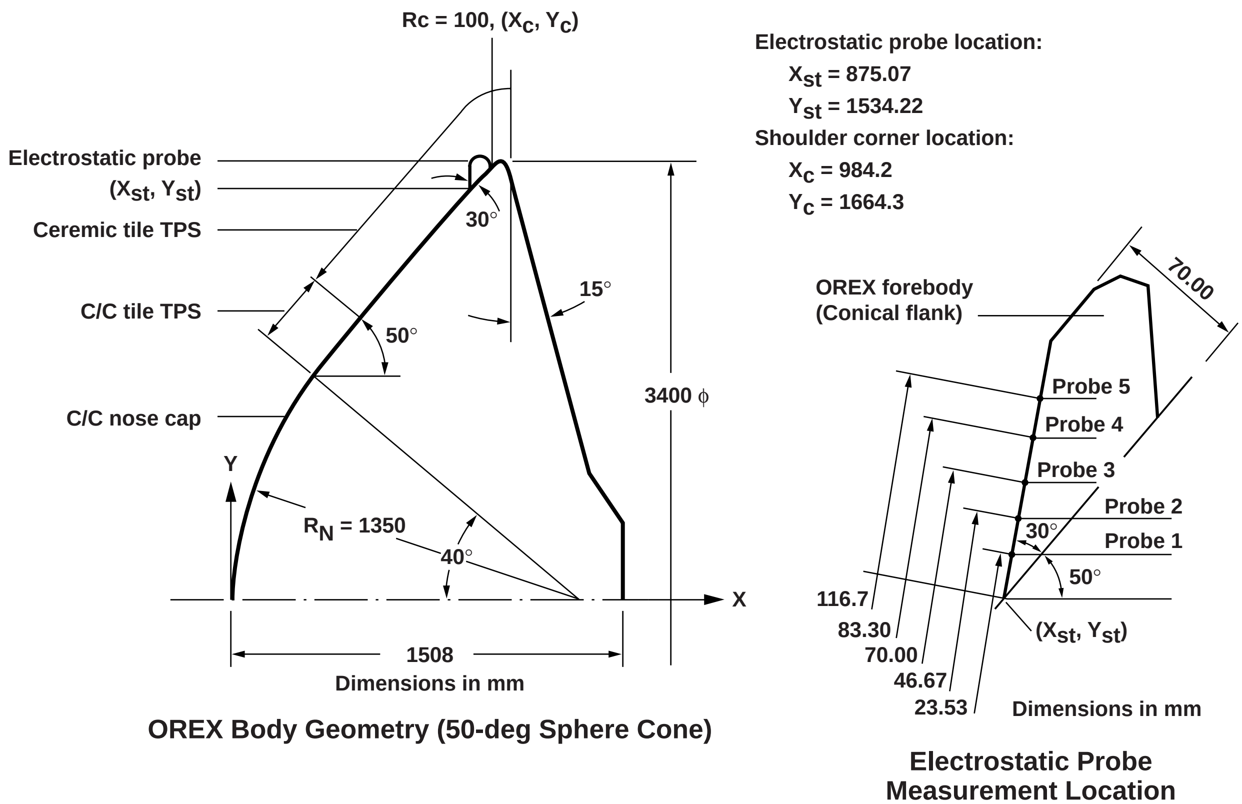

Figure 1. OREX shape and electrostatic measurement locations.

Table 1. OREX Test Cases, T9-97.1–T9-97.4.

No.	Flight time (s)	Altitude (km)	V_∞ (m/s)	T_∞ (K)	p_∞ (Pa)	Wall
1	7396.0	92.8	7545.0	188.7	0.1086	NCW
2	7461.5	63.6	6223.4	237.1	14.02	NCW
3	7461.5	63.6	6223.4	237.1	14.02	FCW
4	7461.5	63.6	6223.4	237.1	14.02	FRCW

“NCW” stands for non-catalytic wall,
“FCW” for fully catalytic wall, and
“FRCW” for finite-rate catalytic wall.

Table 2. Simulation Models.

Contributor	Grid	Physics	Numerical Method	Convergence
Murray	61 × 41	chem.neq./therm.eq/ncw	FV, ALE	
Palmer & Prabhu	49 × 129	chem.neq./therm.eq./ncw, fcw, frcw	FV, FVS 3rd ord.	
Peigin & Kazakov	41 × 11	chem.neq./therm.eq./ncw, fcw, frcw	FV, high order	PNS

This synthesis is incomplete without a consideration of uncertainties in derived flight data. The influence of measurement uncertainties (table 1 of ref. 1) on derived flight data is not known. The level of numerical accuracy, or the numerical uncertainties, in the inferred temperature distributions and inferred heating rates is not available. Uncertainties in the inferred quantities owing to modeling of the physics are not available. What models were used for modeling natural phenomena are not known.

For Case T9-97.1, velocity slip and temperature slip (the low-density effects) when the Knudsen number is between 0.03 and 1.0 and thermal nonequilibrium (the high-temperature effect) need modeling. The Knudsen number is in this range along a significant portion (roughly 1 m in length) of the surface of ORV. The translational-rotational temperature and the vibrational-electronic-electron temperature are reportedly significantly different through the entire entropy layer along the stagnation streamline (ref. 5). The presented simulations do not account for these effects. The derived flight data probably did not account for these effects.

For all cases, the inferred, stagnation-point heating rates are determined from the temperature measurements made at the back surface of the nose cap, which has a thickness of 4 mm. This determination requires correct thermo-structural modeling of the carbon-carbon (C/C) nose cap, the accounting of effects of heat shield after the nose cap and of contact heat resistance at the measurement point, and so forth. Whether this determination is made correctly is not assessed.

Discussion of Results

Details of the simulation models and of the efforts for establishing the numerical accuracy are provided by the investigators (refs. 7–9). The top-level features are summarized in table 2. No grid-refinement studies were conducted in the direction along the surface of ORV. Relatively speaking, Palmer and Pradhu (P&P) have studied grid sensitivity and convergence issues well (ref. 7). Peigin and Kazakov (P&K) have chosen a simplified simulation model and have used a solution-adaptive procedure in the direction normal to the surface (ref. 8). Murray varied the grid distribution in the direction normal to the wall of ORV, while keeping the total number of points fixed (ref. 9). P&P and Murray capture the bow shock wave; P&K fit this shock. P&K require significantly fewer grid points in the region between the bow shock wave and the surface of ORV to produce results comparable to those of P&P. P&P and Murray used a seven-species finite-rate chemistry model, and P&K simulated air with a five-species model. What methods are used for deriving the heat-transfer rates from computed results of the governing equations is not known. Differences in methods may introduce errors in comparisons of rates.

Table 3. Test Case T9-97.1 (92.8 km, NCW)

Contributor	p_{stag} (Pa)	q_{stag} (W/m^2)	T_{max} (K)
Murray	107.34	98352	13806
Peigin & Kazakov	108.37	98974	16621
Inferred Flight Data	N.A.	≈100000	N.A.

Table 4. Test Case T9-97.2 (63.6 km, NCW)

Contributor	p_{stag} (Pa)	q_{stag} (W/m^2)	T_{max} (K)
Murray	7594.06	121096	5201.56
Palmer & Prabhu	7810	262000	10368
Peigin & Kazakov	7599.4	227060	13077
Inferred Flight Data	N.A.	416000	N.A.

Table 5. Test Case T9-97.3 (63.6 km, FCW)

Contributor	p_{stag} (Pa)	q_{stag} (W/m^2)	T_{max} (K)
Palmer & Prabhu	7810	593000	10333
Peigin & Kazakov	7590.8	537170	13078
Inferred Flight Data	N.A.	416000	N.A.

Table 6. Test Case T9-97.4 (63.6 km, FRCW)

Contributor	p_{stag} (Pa)	q_{stag} (W/m^2)	T_{max} (K)
Palmer & Prabhu	7811	416000	10407
Peigin & Kazakov	7599.4	401500	13078
Inferred Flight Data	N.A.	416000	N.A.

The results provided by P&P and P&K to Marco Marini, Centro Italiano Ricerche Aerospaziali (CIRA, Italy), at the time of the workshop are presented herein. P&P's results, as presented herein and in their paper (ref. 7), are identical. P&K's results in this synthesis and in their paper (ref. 8) are slightly different. For example, heat-transfer rates presented in tables 3–6 are 98.974, 227.060, 537.170, and 401.500 kW/m^2 for Cases T9-97.1, T9-97.2, T9-97.3, and T9-97.4, respectively. In P&K's paper, the corresponding numbers are 98.975, 227.2, 537.4, and 410.3 kW/m^2. These differences are considered negligible. However, there are differences between p_{stag} and p_{wmax} (which is equal to p_{stag}) as reported here and in ref. 8, respectively. These differences are assumed to result from differences in normalization.

Murray investigated Cases T9-97.1 and T9-97.2. There is a minor difference between what was presented for Case T9-97.1 at the workshop and that presented in ref. 9. For example, at the workshop, q_{wmax} was 98.401 kW/m^2 and in ref. 9 it is 95.074 kW/m^2. The maximum heating rate is not at the stagnation point, but at the first grid point off the stagnation point. Figure 2 of ref. 9 suggests that the heat-transfer rate at the stagnation point is close to but lower than the maximum heating rate. The estimated value of q_{stag} is 95.025 kW/m^2. In this synthesis, Murray's results, submitted at the time of the workshop, are considered.

Murray's values for q_{stag} and T_{max} (maximum temperature along the stagnation streamline) as reported in table 4 (Case T9-97.2) are significantly different from those of P&P and P&K and from inferred flight data. Among Cases T9-97.2–T9.97.4, the finite-rate catalytic wall condition is meaningful, because of a much better agreement with inferred flight heating rate. Additionally, Murray's results in ref. 9 and those in table 4 are different. The latter data were the ones he submitted to Marco Marini at the time of the workshop. In ref. 9, p_{stag}, q_{stag}, and T_{max} are, respectively, 1381.0 Pa, approximately 121.164 kW/m^2, and 6337 K, respectively. For these reasons, Murray's results for Case T9-97.2 are not discussed further in this synthesis; interested readers are referred to ref. 9.

For Case T9-97.4, P&P found a recombination coefficient value of 0.004 to produce a computed stagnation-point heating rate that matched inferred flight data. P&K have estimated this coefficient to be 0.0053. P&P could have obtained a different value for this coefficient, if they had further refined the distribution of points in the direction normal to the surface (see fig. 2a in ref. 7). P&K used a solution-adaptive procedure for the distribution of 11 points in the normal direction; they did not vary the total number of grid points in that direction. Additionally, P&P and P&K used different phenomenological models without determining their sensitivity. For these reasons, probably neither set of computed results is independent of numerics and of the modeling of natural phenomena. Therefore, it is not surprising that different values of the recombination coefficient are obtained.

The main observations concerning the comparisons presented in tables 3–6 are (1) for the materials used on the surface of ORV, the finite-rate catalytic wall condition is the correct condition for predicting low-altitude heating rates, and the non-catalytic wall condition is appropriate at high altitudes; (2) the determination of the correct value of the maximum temperature along the stagnation line requires additional research; and (3) the pressure at the stagnation point may be predicted within about three percent.

In Figures 2–10, mostly P&P's results with the non-catalytic wall condition and P&K's results with the finite-rate catalytic wall condition are emphasized (for the sake of clarity), when results for the altitude of 63.6 km with different wall catalyticity are almost the same. P&K's results are also emphasized over those of Murray for the altitude of 92.8 km.

The major observations concerning the surface quantities (figs. 2–4) are the following: (1) pressure profiles and skin-friction distributions are insensitive to the wall catalyticity at low altitudes; (2) all investigators need to further study grid sensitivity and simulation-model (numerical, physics, and chemistry models) sensitivity for assessing the credibility of simulated realities, as discussed in refs. 10 and 11; and (3) much more flight data (raw and derived), along with their uncertainties, are needed for validating simulated reality.

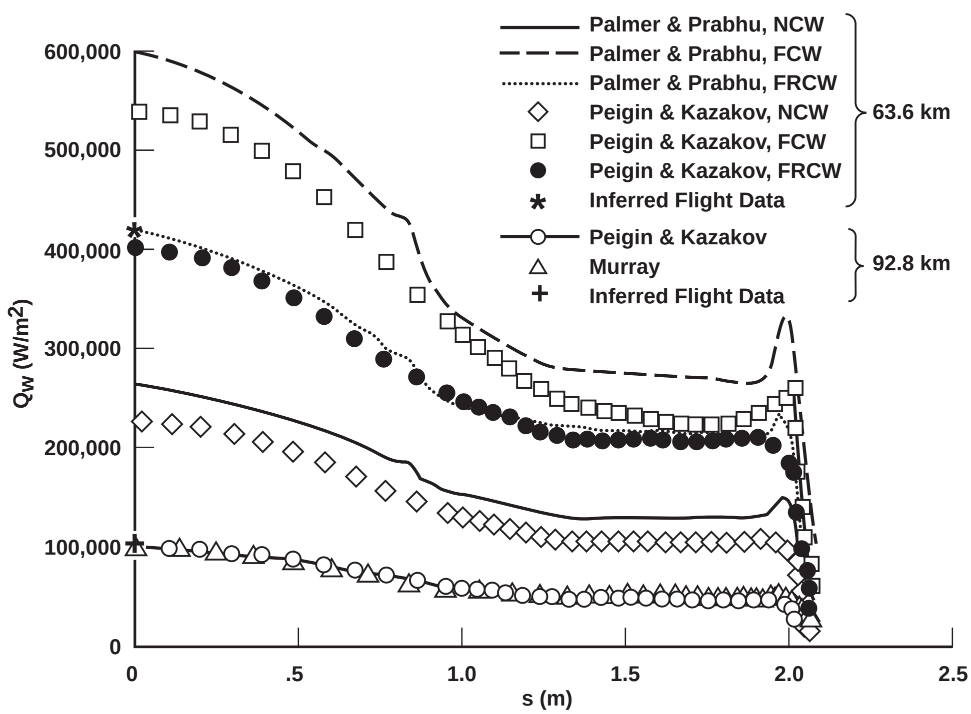

Figure 2. Heating-rate distributions along the surface.

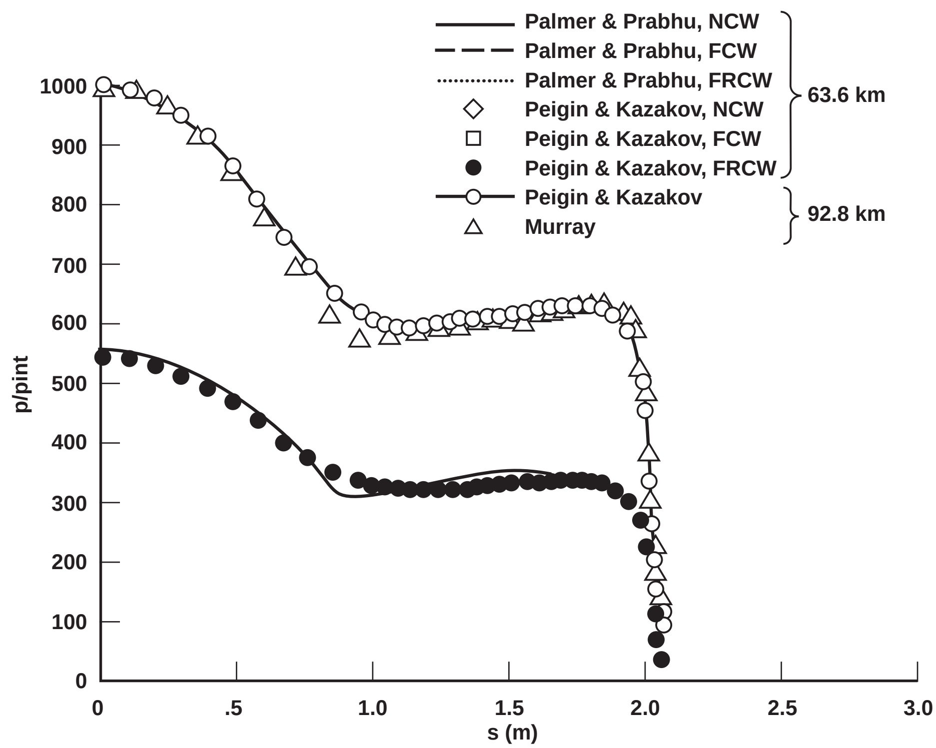

Figure 3. Pressure distributions along the surface.

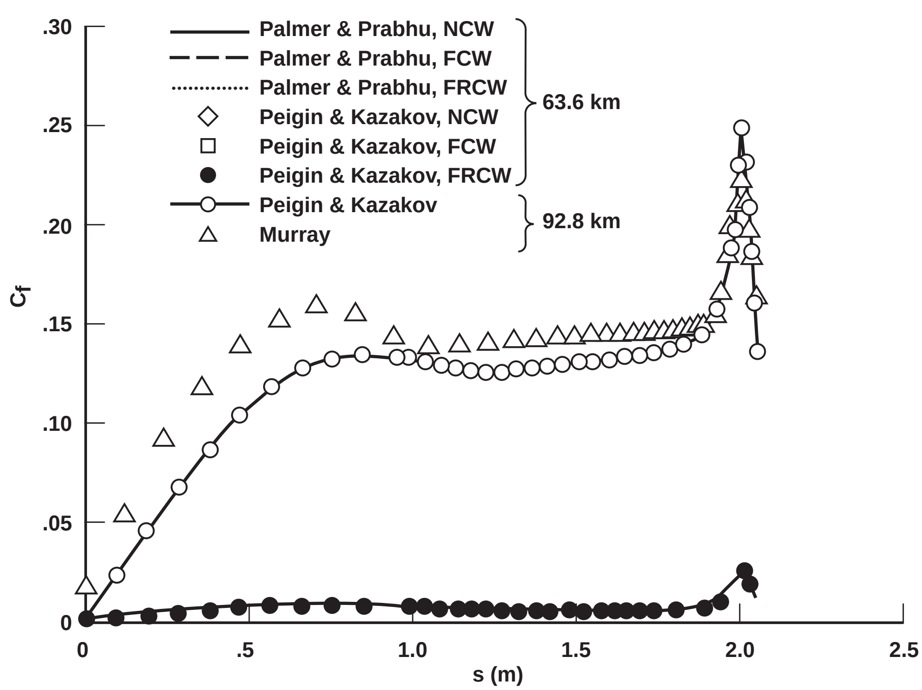

Figure 4. Skin friction distributions along the surface.

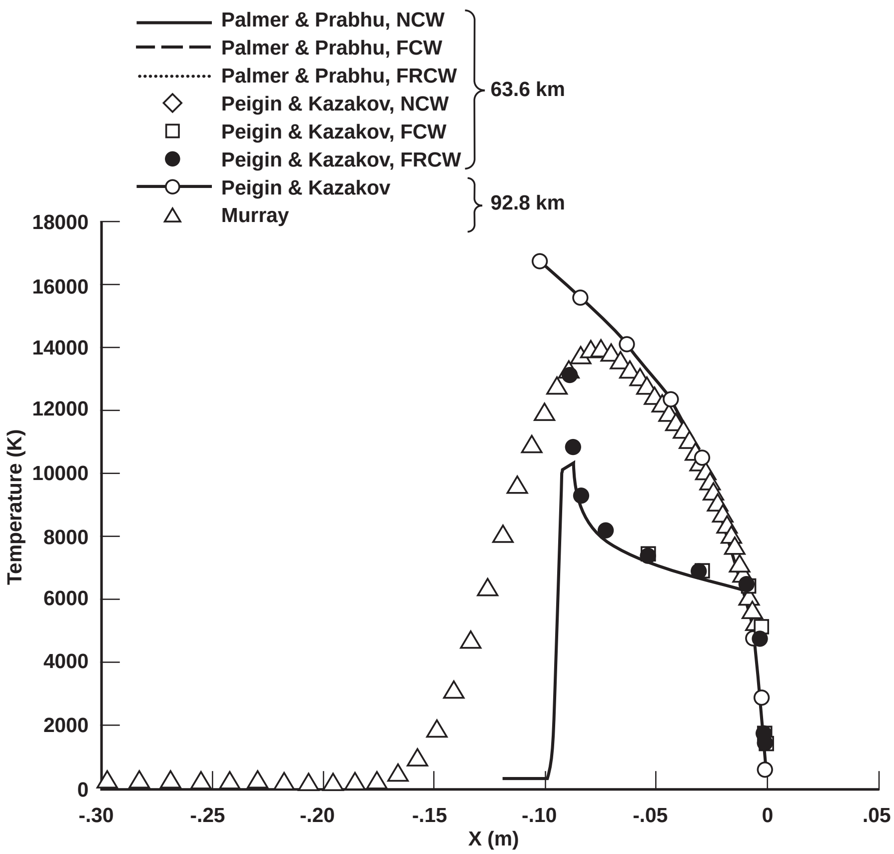

Figure 5. Temperature distributions along the stagnation streamline.

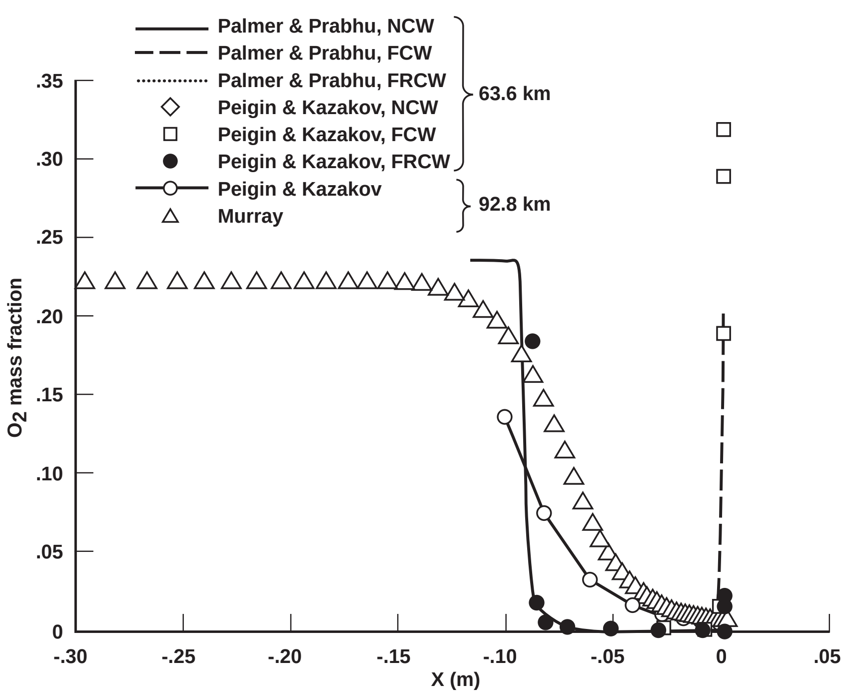

Figure 6. O_2 mass-fraction distributions along the stagnation streamline.

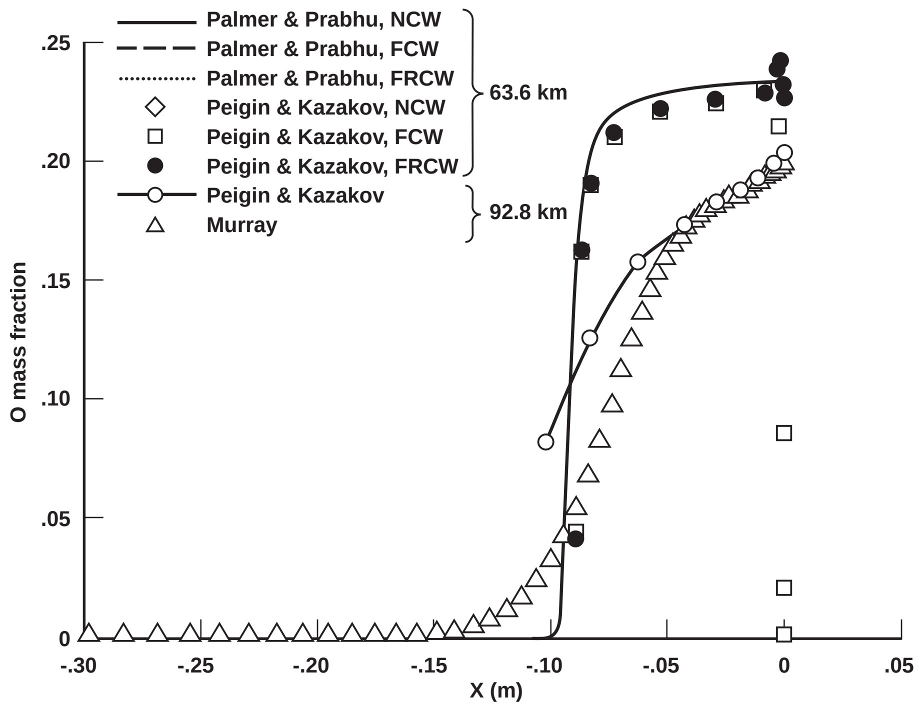

Figure 7. O mass-fraction distributions along the stagnation streamline.

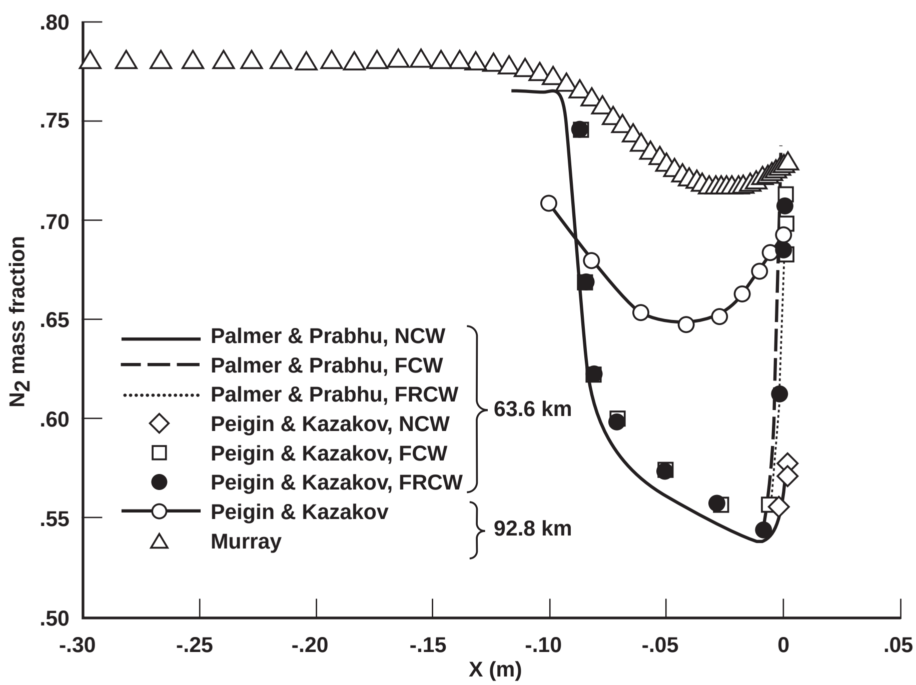

Figure 8. N_2 mass-fraction distributions along the stagnation streamline.

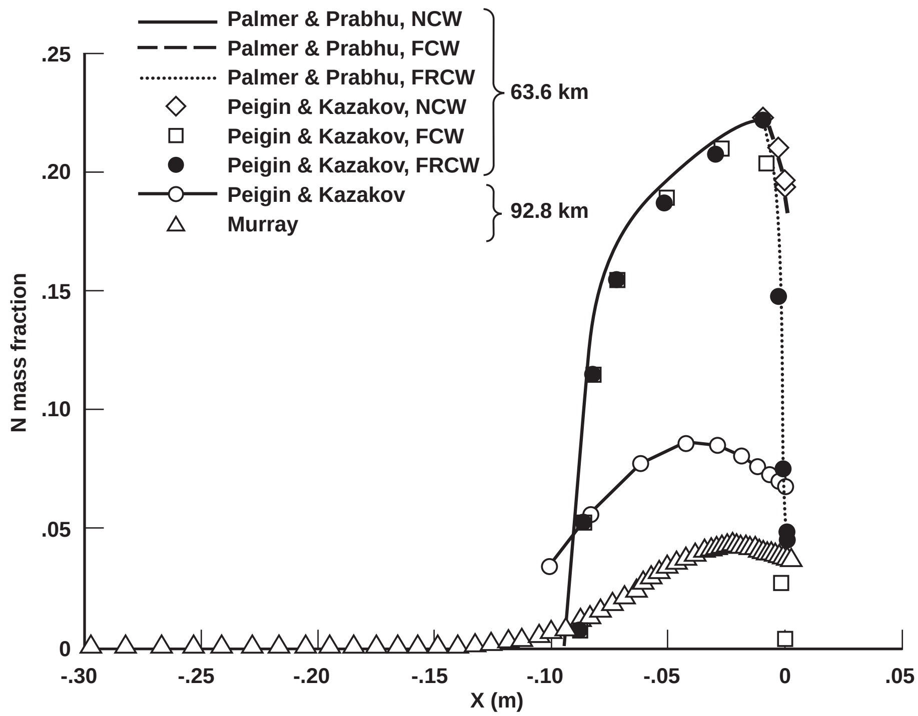

Figure 9. N mass-fraction distributions along the stagnation streamline.

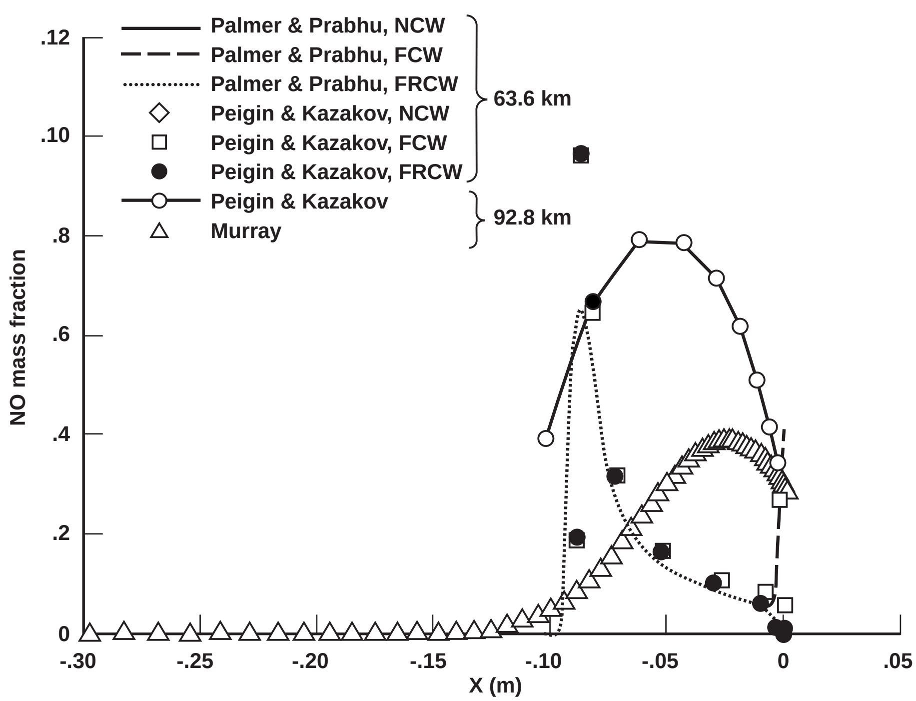

Figure 10. NO mass-fraction distributions along the stagnation streamline.

The temperature distribution across the shock wave is sensitive to the way in which this wave is modeled (fig. 5). Murray's simulation model is significantly more dissipative than that of P&P. The thickness of the entropy layer at the stagnation point as computed by P&P is comparable to that computed by P&K.

At the altitude of 63.6 km, comparisons of mass fractions of various species (figs. 6–10) confirm the sensitivity of species concentrations near the surface of ORV to the wall catalyticity. P&K did not take ionization into account for Case T9-97.1; Murray did. Murray reports maximum electron number density as being 7.06 x 10^{11} either per cubic meter or per cubic centimeter—ref. 9 does not specify the unit of volume. The maximum electron number density from derived flight data is approximately $10^{17.5}$ per cubic meter (refs. 1 and 5). Although the surface heat-transfer rates and surface-pressure distributions of P&K and of Murray are comparable, their species mass fractions are significantly different. A sensitivity study of the chemistry modeling is recommended.

Conclusions

1. To properly assess the credibility of computer simulations, an assessment of the quality of the derived data from OREX is needed.

2. Computer simulations for the high-altitude case are uncertain because the sensitivity of simulations to low-density effects, to high-temperature effects, and to the number of species and reactions is not investigated.

3. For the low-altitude case, the comparison of computer simulations and the flight data suggest that the finite-rate catalytic wall assumption is appropriate under OREX conditions.

4. Solution-adaptive simulations, grid-refinement studies, and investigations of the sensitivity of the physics and chemistry modeling are essential for any simulation.

5. The results of Peigin and Kazakov and those of Palmer and Prabhu appear acceptable for test case T9-97.4. It is quite encouraging that both teams got very similar results with fundamentally different methods. Additional sensitivity studies are required to establish the level of accuracy of these results. Murray's results are questionable.

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